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# Comparision of Options for Reduction of Noise in the Test Section of the NASA Langley 4 x 7m Wind Tunnel Including Reduction of Nozzle Area

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# ADDITIONAL OPTIONS FOR REDUCTION OF NOISE IN THE TEST SECTION OF THE NASA LANGLEY 4 X 7m WIND TUNNEL

## I. OVERVIEW

NASA is studying the possible modification of the 4x7m wind tunnel at Langley Research Center to provide the necessary acoustic environment for aeroacoustic studies of model helicopter rotors (and possibly other devices). A thorough study of the existing acoustic characteristics of the 4x7m wind tunnel has been carried out, along with means for reducing the background noise in the test section to the desired levels (Ref. 1). This document summarizes key findings of that study, provides additional data on the reference "state-of-the-art" quiet open-jet wind tunnel (the DNW Low Speed Tunnel, Holland), and also introduces a new approach to achieving NASA's goals at much less cost and with much less impact on the 4x7m tunnel circuit and ongoing operations than previously-proposed approaches.

The study described in Ref. 1 reached several major conclusions:

- the background acoustic levels in the 4x7m wind tunnel exceed NASA's goal by as much as 40 dB;

- the test chamber acoustic characteristics are unacceptable for most measurements which would be typical of rotor tests carried out in the 4x7m tunnel; therefore, a high quality anechoic space is a prerequisite to achieving the acoustic goals for the 4x7, tunnel;

- the tunnel fan operates in a stalled condition, at low efficiency and at a relatively high tip speed, and is the dominant noise source in the circuit;

- noise from the fan propagates to the test section approximately equally in the upstream and downstram directions; therefore, both parts of the tunnel must be

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treated extensively to attenuate sound generated by the
existing fan;

- noise from turning vanes (first and second corner) is
  not dominant but presents a barrier to reaching the
  background noise goal;

- turning vanes will probably serve as waveguides to high
  frequency sound (i.e., frequencies at which the acoustic
  wavelength is equal to or smaller than the vane's chord)
  and thus cause bypassing of acoustic treatment applied
  to the tunnel walls or to parallel baffle silencers;

- numerous noise control options exist for reducing the
  primary contributions to background noise in the test
  section; these approaches can be categorized as follows:
  - source reduction (fan and vane redesign)
  - non-intrusive wall treatments (absorption)
  - treated splitters, baffles, and turning vanes

- the predicted cost of providing a high quality acoustic
  space in the 4x7m test chamber, and reducing the back-
  ground noise by optimum combinations of the above-listed
  approaches is in the range of $4.5-5.5M, exclusive of
  additional research, development, and preliminary
  engineering;

- model tests are needed to remove remaining ambiguities
  about source/path contributions, provide data for
  redesign of the fan, and aid in acoustic and aerodynamic
  optimization of various treatments.

An alternate concept for achieving the objectives for rotor
testing in the 4x7m tunnel is to reduce the size of the nozzle
exit through the use of portable extensions to the existing
nozzle. Appendix B of this document provides estimates of the
nozzle size required and noise reduction achievable, showing that

for the 1.82m (6 ft) rotors, only a 6.82m$^2$ opening is required; this reduced area and attendant reduced flow requirement should lead to a total elimination of fan and turning vane noise contributions to the test section background levels. This concept can be implemented for a total estimated cost of less than \$1.4M (including a full anechoic treatment for the test chamber). The nozzle opening required for the largest rotors of interest 2.72m (9 ft) in diameter, is around 15m$^2$; some circuit noise control is required for this concept, but the total estimated cost of the complete "acoustic" treatment is still less than \$2.5M.

Section 2 of this document provides key details of the existing environment and noise control goals. Section 3 summarizes approaches to circuit noise control, including the "reduced-nozzle-size" approach. Section 4 summarizes the impacts of the various options, and Section 5 summarizes recommendations.

Appendix A provides a comparison of key acoustic features of the NASA 4x7m tunnel and the DNW tunnel, which is often cited as the reference state-of-the-art large quiet aeroacoustic facility.

Appendix B describes the rationale for and predicted performance of the "reduced-nozzle-size" approach to meeting the 4x7m tunnel acoustic objectives.

## 2. EXISTING ENVIRONMENT AND GOALS

### 2.1 Acoustic Space

Figure 1 (from Ref. 1) illustrates the problem with the existing test chamber; namely, excessive reflections from nearby surfaces. Measurements of spatial variation of pure tones in the room showed ±15 dB fluctuations, which is totaly unacceptable. An extensive and high quality treatment of all surfaces in the room, including the collector, floor, ceiling, and control room is required.

### 2.2 Background Noise Levels

Figure 2 illustrates the existing background noise levels in the 4x7m test section relative to a goal established by a NASA study committee. Also shown for comparison are levels measured in the DNW tunnel for the same tunnel speed (see App. A).

It is evident that the 4x7m acoustic levels are well above those required by NASA and also those achieved by DNW. The principal reasons for the high levels relative to DNW are: (1) extreme differences in fan loading, (2) acoustic treatment built into the DNW circuit, and (3) test section absorption (DNW has full anechoic treatment) (see App. A for further details of these comparisons).

Also shown in Figure 2 is a range of estimated flow-induced ("self-noise") pressure levels for current (and postulated future) condensor microphones mounted in streamlined housings. The significance of this result is that the flow-induced levels exceed the in-flow noise goal established by NASA. Thus, either this goal should be reconsidered, or development of advanced acoustic sensors with low response to turbulent flow should be initiated so that meaningful in-flow acoustic measurements can be made.
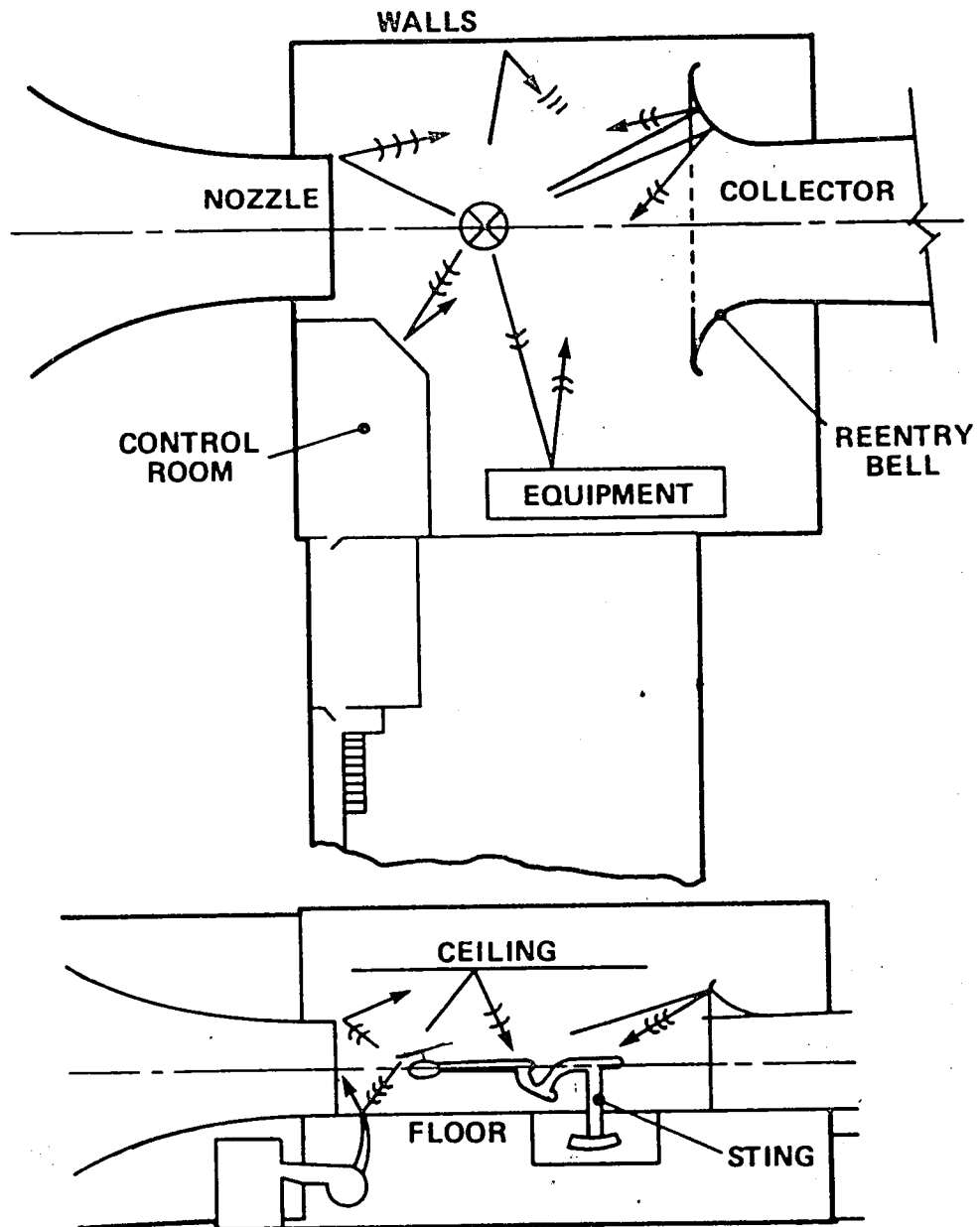
FIGURE 1. SCHEMATIC OF REFLECTIONS FROM SURFACES IN THE 4X7m WIND TUNNEL TEST SECTION (FROM REF. 1)

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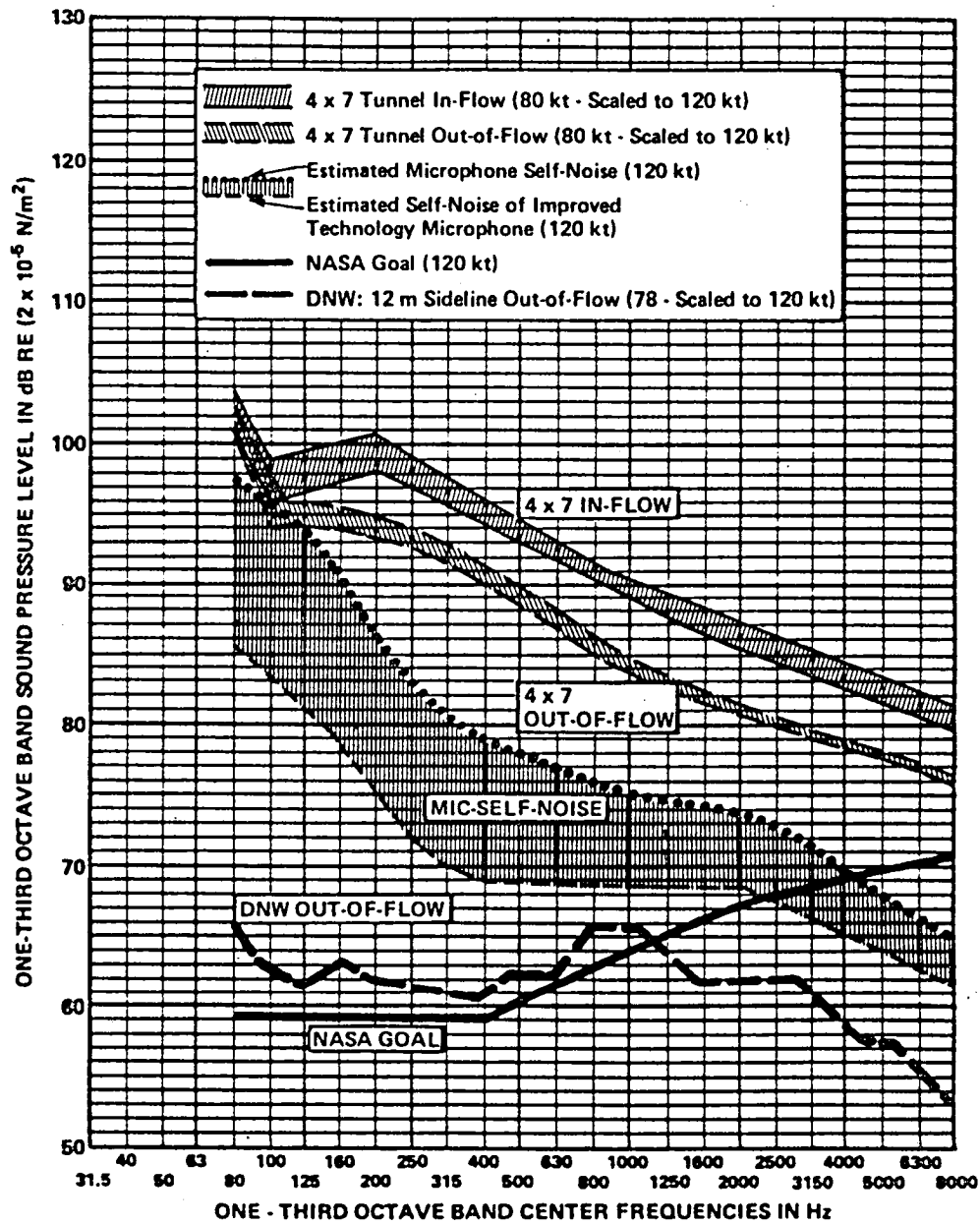
FIGURE 2. COMPARISON OF EXISTING BACKGROUND NOISE LEVELS WITH NASA GOALS, DNW LEVELS, AND IN-FLOW MICROPHONE SELF-NOISE.

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The predicted source-path contributions are shown in Figure 3, revealing the fan as the dominant source followed by first and second corner turning vanes. For the fan source, both upstream and downstream paths require treatments with comparable insertion loss; for the first corner vanes, only the upstream path needs to be treated if the fan downstream path is also treated. Noise from second corner vanes will not require treatment if treatments are in place to control fan and first corner noise.

If the "reduced-nozzle-size" approach is taken, treatment of the auxiliary machinery noise will be required since little or no circuit attenuation will exist (see Sec. 3).
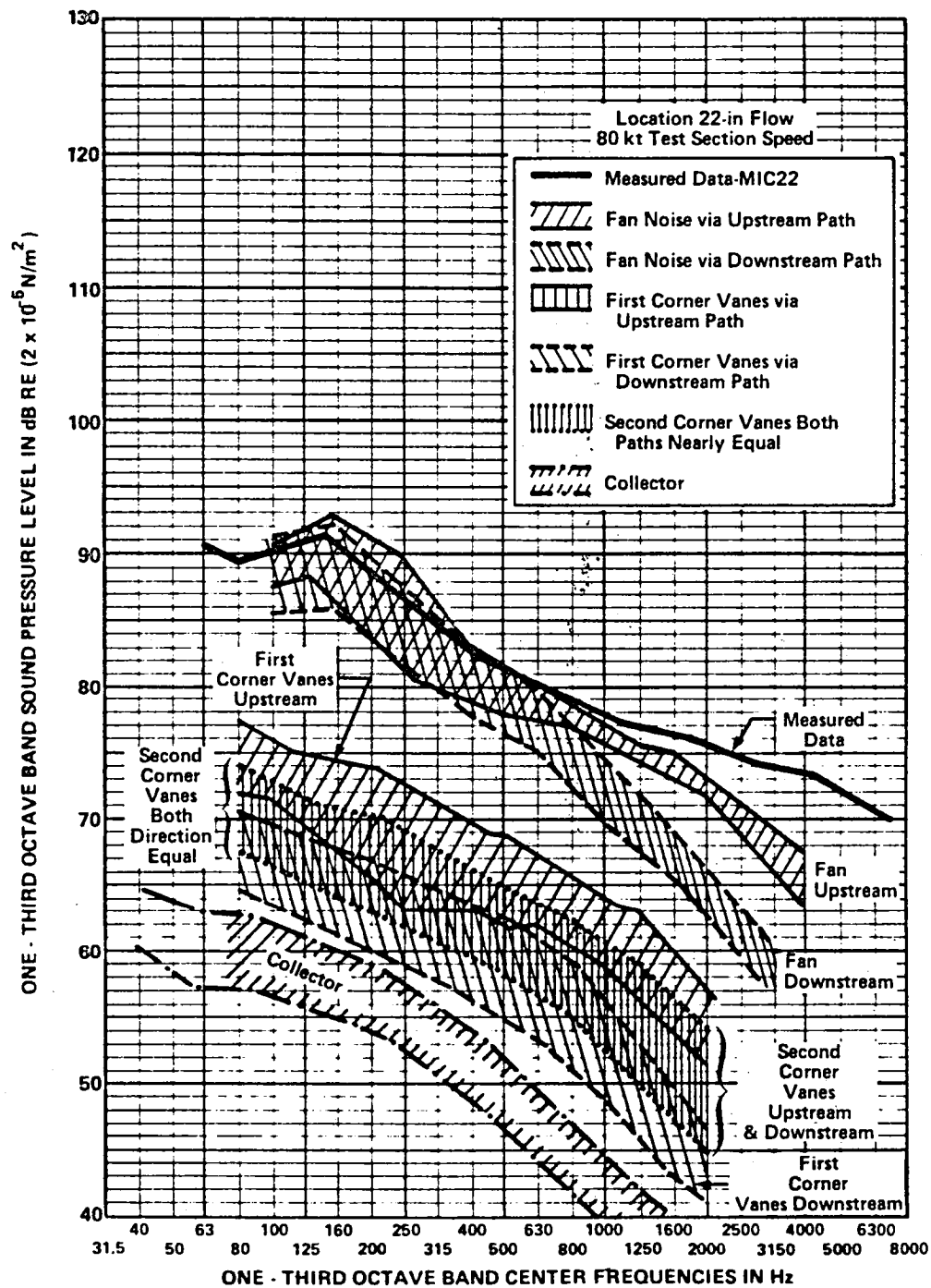
**FIGURE 3. PREDICTED SOURCE–PATH CONTRIBUTIONS TO BACKGROUND NOISE IN TEST SECTION**

## 3.  NOISE CONTROL APPROACHES

### 3.1  General Approach

The reductions in levels required of the various circuit noise sources can be achieved by modifying the source, or by absorbing sound along the circuit.  Both approaches were explored in Ref. 1, and the optimum combinations devised utilized both source reduction and path attenuation.  Appendix B herein introduces a new concept which reduces the background sound in the test section strictly through reduction of source levels; this is achieved by significant reduction of mass flow through the circuit achieved by a reduction in the nozzle size.

### 3.2  Source Reduction

The 4x7m tunnel fan operates in a stalled condition due to excessive loading of the tip region of the blades.  The excessive loading results from large scale irregularities in the inflow to the fan rotor, most notably a large velocity deficit on the inside part of the flow path.  The stall can be eliminated by modification of inflow velocity profiles and/or altering the blades' pitch and chord distribution.  Stall elimination alone will reduce noise levels by at least 8-10 dB, and further reductions in local blade loading could produce as much as 15 dB additional noise reduction (by extensive blade redesign).

Turning vane source levels can be reduced by reduction in local flow velocity, reducing turbulence levels, or lengthening of vane chord in conjunction with addition of an airfoil section with a significant leading edge radius.  Lengthened airfoil-shaped turning vanes are also a prime means of absorbing sound in the circuit (see below), and therefore can concurrently reduce vane source levels while absorbing sound from other sources.

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## 3.3 Path Treatment Concepts

Path treatments must provide good low- and mid-frequency performance while minimizing aerodynamic losses and self-noise generation. A particularly difficult problem in the 4x7m wind tunnel is achieving good acoustic performance in the mid-frequency range (500 Hz-1 kHz octave bands) (Ref. 1). This is due to the large cross-sectional dimensions of the ducts; at 1 kHz and above, another problem is introduced - waveguiding by turning vanes which caused sound waves to bypass wall and parallel baffle treatments, although <u>treated</u> vanes can reduce the levels of high frequency sound transmitted by such waveguiding.

Path treatment concepts studied in Ref. 1 included:

- flat non-intrusive wall treatments;
- simple streamlined baffles;
- parallel-baffle silencers;
- cruciform-baffles;
- "ring" and centerbody treatments upstream and downstream of the fan
- long-chord treated turning vanes.

None of the above concepts provided adequate insertion loss across the entire frequency band. Therefore, several combinations were devised and analyzed in terms of cost-effectiveness. The recommended options are summarized below.

## 3.4 Recommended Combinations of Circuit Path Treatments

Figure 4 presents schematically two approaches to achieving the needed circuit noise reduction and improvement in test section acoustic quality.

Scheme A in Figure 4 contains the following features:

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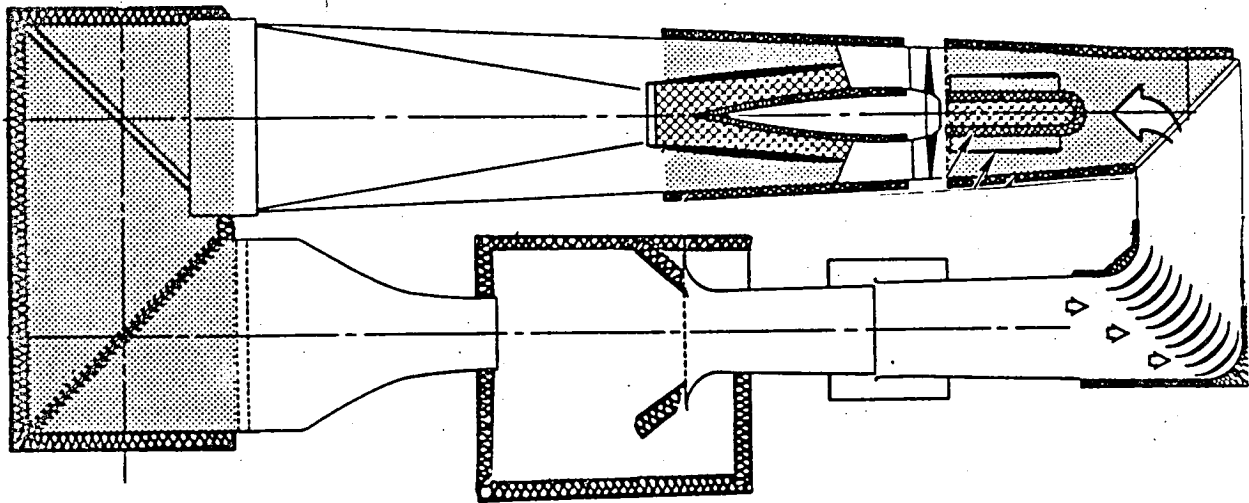
Scheme A (no fan redesign)
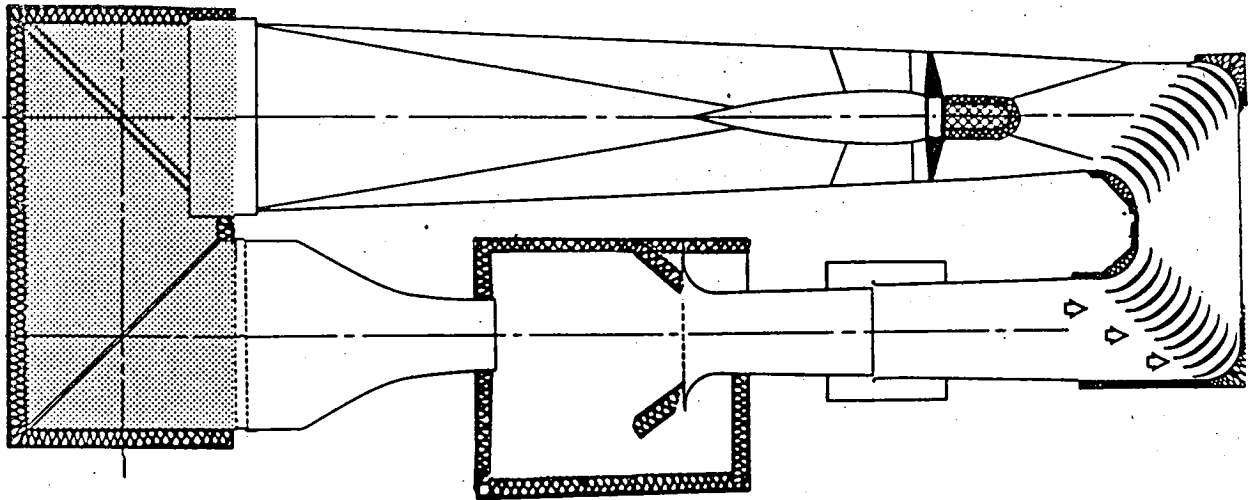
Scheme B (significant fan redesign)

FIGURE 4.   TWO "OPTIMIZED" APPROACHES TO ACOUSTIC TREATMENT OF
THE 4X7m TUNNEL CIRCUIT

- anechoic treatment in test section;

- absorption added to collector surfaces;

- long-chord treated vanes in the first corner;

- fan inlet treatment consisting of a lined wall, a long treated nose cone, and a streamlined-treated splitter ring;

- fan exhaust treatment consisting of the same elements as the inlet treatment;

- a lined settling chamber ("second crossleg");

- treated airfoil-shaped fourth corner vanes.

If the fan can be unstalled by tailoring the shape of the nose cone, it may be possible to reduce the extent of wall treatment or to omit it entirely.

Scheme B in Figure 4 illustrates the treatment required for the case where the fan has been redesigned to operate unstalled and at approximately 50% of its present tip speed. The fan redesign requires new blading (longer chord, and pitch settings tailored to local inflow), and the addition of a nose cone. The additional absorptive elements required in the circuit include:

- anechoic treatment in the test section;

- absorption added to the collector surfaces;

- treated first corner vanes

- treated (elongated airfoil-shaped) second corner vanes;

- lined settling chamber surfaces.

In Scheme B, it may be possible to reduce or eliminate second corner treatment if noise reduction of the redesigned fan exceeds present estimates slightly; also, a single vertical treated

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splitter may be required in the settling chamber to provide additional low frequency attenuation if noise levels of the redesigned fan are slightly above current estimates.

The estimated cost of Scheme A is $5-5.5M; the estimated cost of Scheme B is $4.5-5M. Both estimates are subject to revision after refinement of engineering details.

## 3.5 Performance of Reduced Nozzle Size Approach

Figure 5 illustrates the implementation of the concept described in Appendix B of this document - use of a reduced nozzle opening in order to allow lower fan speeds and thus lower fan noise. To the first order, the fan tip speed can be reduced in direct proportion to the nozzle area (see App. B.), <u>if circuit losses are dominant</u> over those associated with the creation and collection of a partially-open jet. The minimum nozzle area required to test a 1.82m (6 ft) rotor is $6.82m^2$, and the area required to test a 2.72 (9 ft) rotor is $15.1m^2$. These areas represent a 76.5% and 48% reduction in nozzle area (and thus circuit mass flow).

The background noise reduction achieved in the test section with the various nozzles can be illustrated by a series of three plots shown in Figures 6-8. Figure 6 shows the test section noise levels in the present 4x7m tunnel; also shown is the NASA goal for background noise and the contribution of auxiliary machinery associated with the fan operation (the significance of the latter will be illustrated below). Figure 7 shows the predicted background noise in the test section for the "treatment" scheme consisting of a $6.82m^2$ nozzle (for 6-ft rotors), and full test section anechoic treatment. The range of noise levels shown for the fan covers the range of levels for stalled and unstalled fan operation, and in-flow and out-of-flow microphone locations. It is apparent that the only residual source to treat will be the

97.49
(320.00)

—— NOZZLE A = 2.2 x 3.1 m = 6.82 m² POSSIBLE PORTABLE
---- NOZZLE B = 3.25 x 4.64 = 15.1 m² ADDITION TO
PLANNED COLLECTOR

├ 20' ┤
APPROXIMATE
SCALE
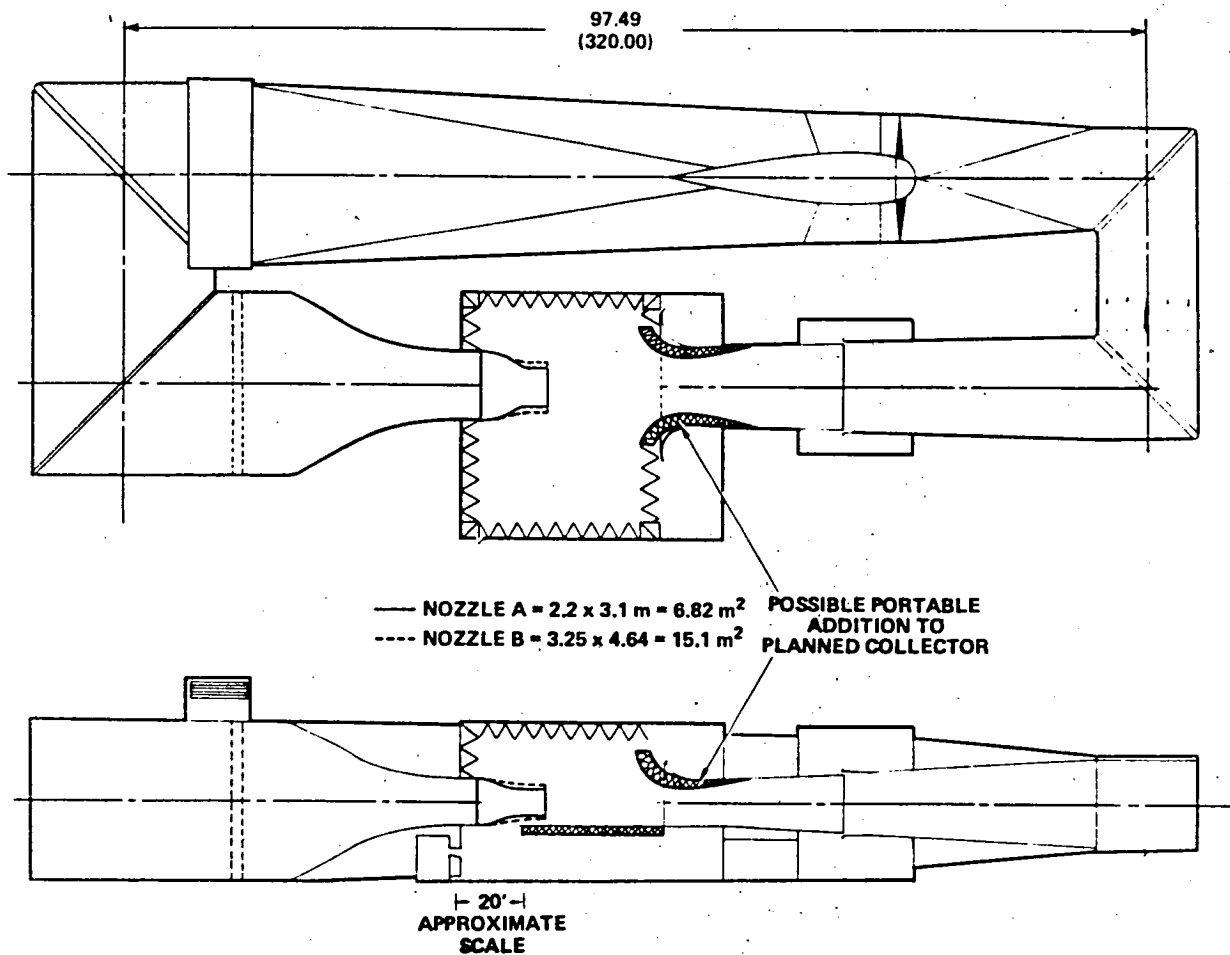
FIGURE 5.   SCHEMATIC OF REDUCED-NOZZLE-SIZE APPROACH TO REDUCING
BACKGROUND NOISE IN THE 4X7m TUNNEL (SEE APP. B FOR
SECOND SCHEME

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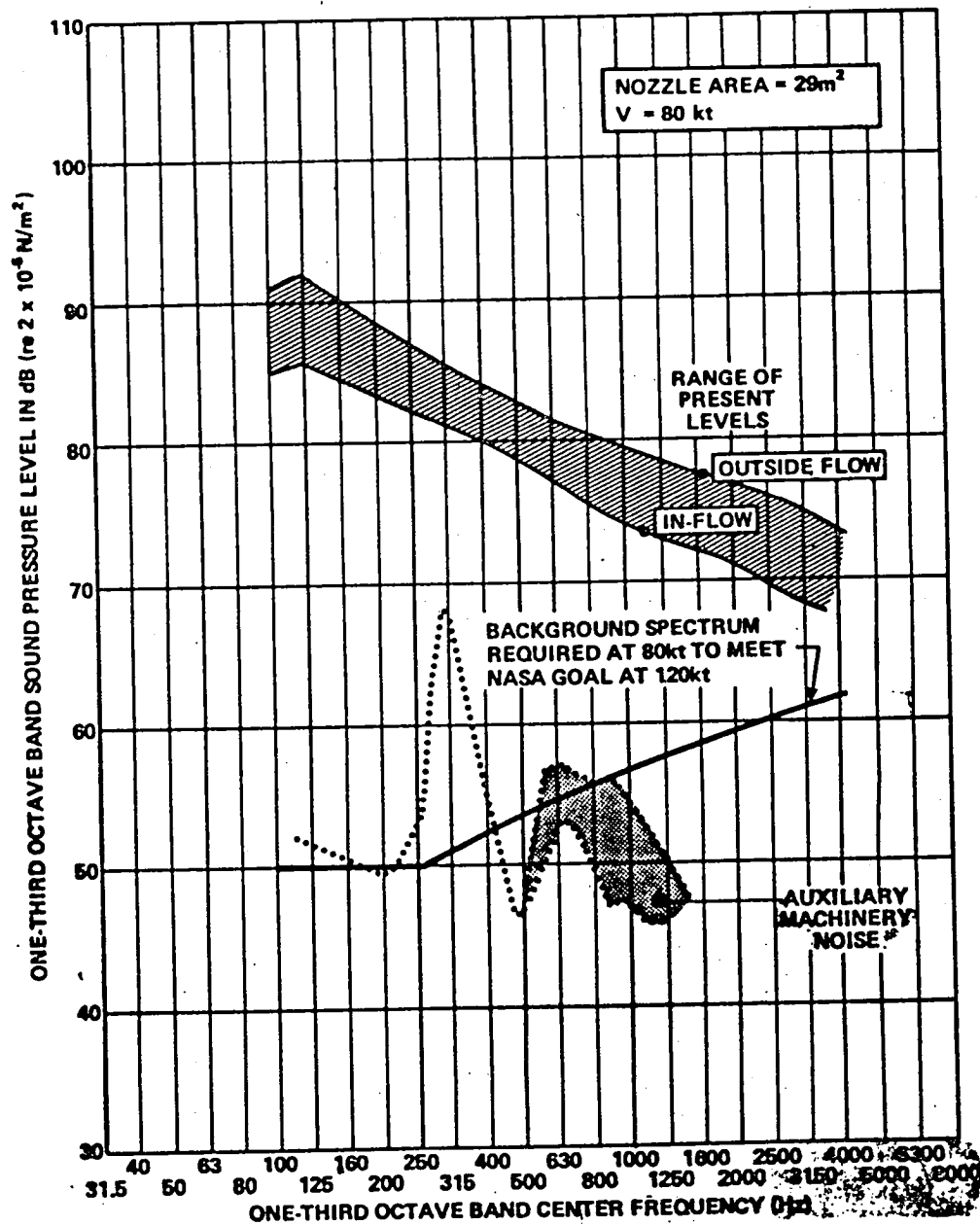
FIGURE 6. BACKGROUND NOISE IN FULL SIZE TEST SECTION OF 4X7m TUNNEL

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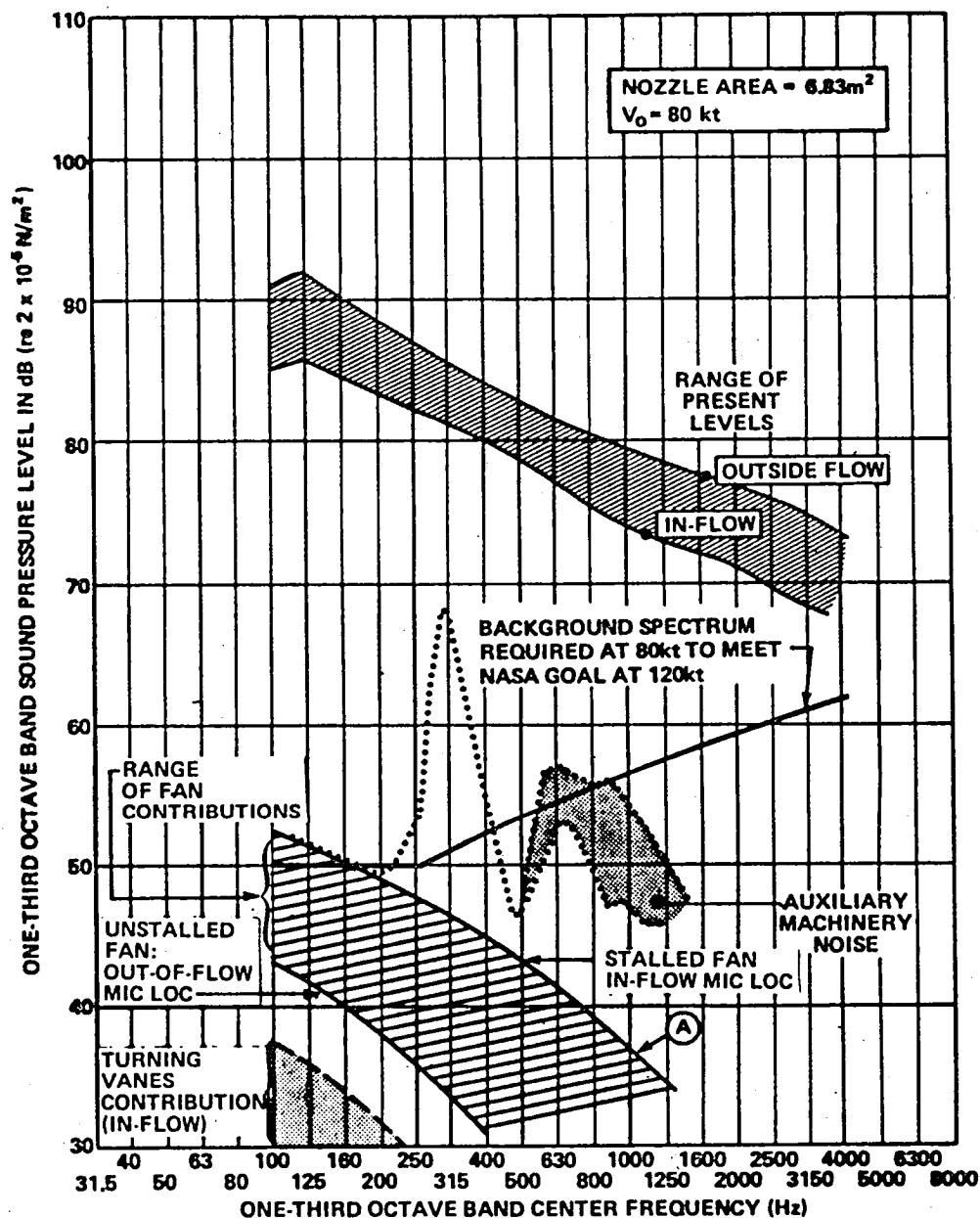
FIGURE 7. PREDICTED BACKGROUND NOISE IN 4X7m TEST SECTION WITH NOZZLE SIZE APPROPRIATE TO TESTING 1.82m (6 FT) ROTORS.

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auxiliary machinery (and possibly test-section-or-collector-flow-induced noise).

Figure 8 illustrates the predicted range of test section background noise levels for a treatment scheme consisting of a $15.1m^2$ nozzle (for 9-ft rotors), and full test section anechoic treatment. This figure shows that the fan noise contributions will exceed the NASA goal by as much as 22 dB in the flow or as little as 13 dB outside the flow at low frequencies, and that first corner turning vane contributions might exceed the criterion in the flow below the 250 Hz octave band. Treatments applicable to reducing this residual noise (Ref. 1) are:

- treated first corner vanes; and

- treatment of the surfaces of the settling chamber (second "crossleg");

- isolation of the auxiliary machinery noise at 315 Hz.

Provision should also be made for a nose cone to eliminate fan stall (and thus reduce levels by 8-10 dB) and a splitter in the second crossleg (settling chamber) to provide additional low frequency attenuation if fan stall elimination does not provide sufficient low frequency reduction.

The estimated cost of Scheme A (using $6.82m^2$ nozzle for 6-ft rotors) is $1.4M, including an estimated $1M for the treatment of the test section.

The estimated cost of Scheme B (using the $15.2m^2$ nozzle) is $2.5M, including $1M for the hall treatments.

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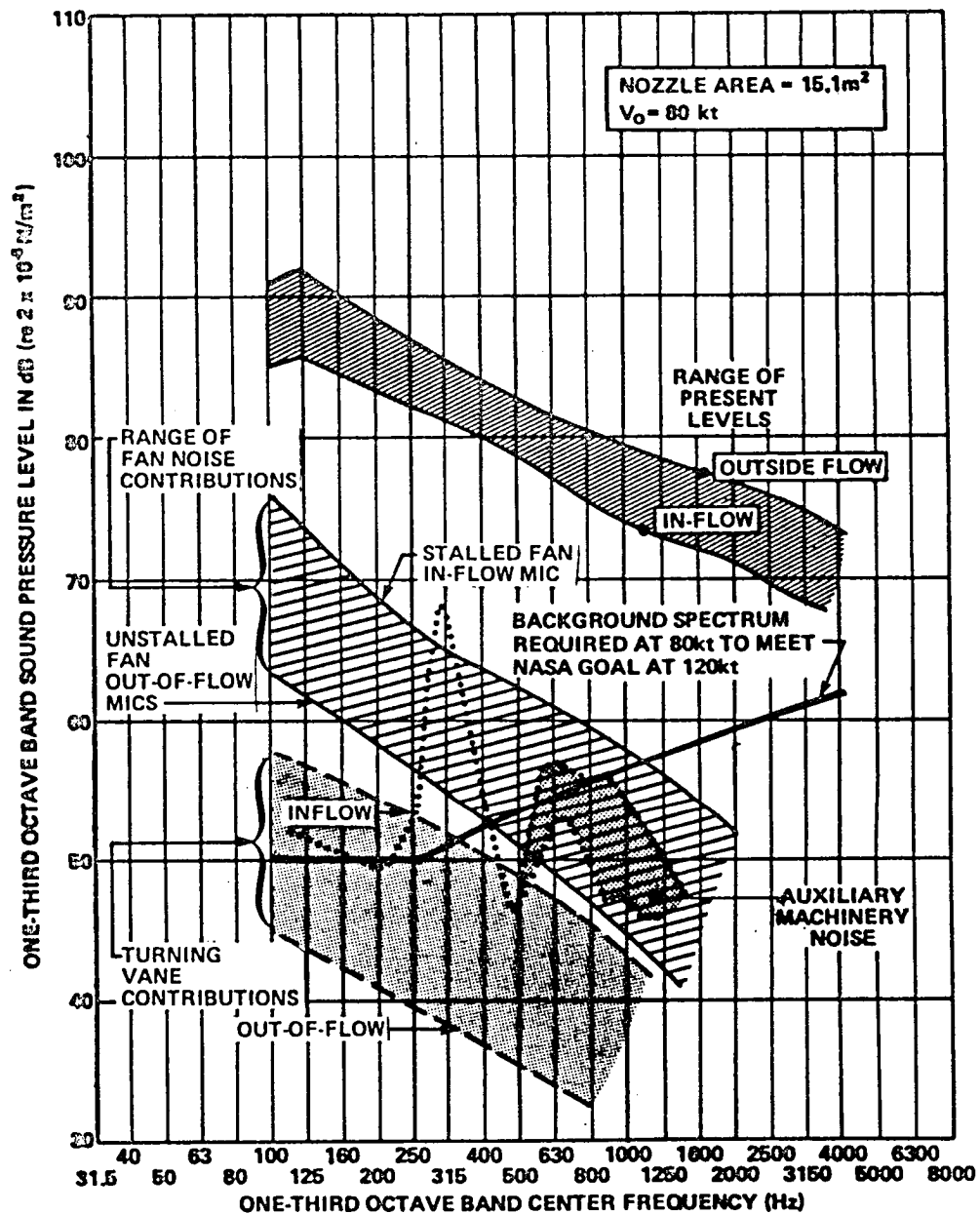
FIGURE 8. PREDICTED BACKGROUND NOISE IN 4X7m TEST SECTION WITH NOZZLE SIZE APPROPRIATE TO TESTING 2.72m (9 FT) ROTORS

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## 4. SUMMARY OF OPTIONS AND IMPACTS

Figure 9 illustrates the four basic options available to achieve the acoustic objectives in the 4x7m test section:

(1) Maintain the current fan and flow path, but test with small nozzles;

(2) Maintain current fan, but add extensive treatment to the circuit;

(3) Rebuild the fan to reduce blade loading and improve efficiency;

(4) Rebuild the fan and add treatment to the circuit.

The impacts of these various choices are summarized in Figure 10.

The first option has the advantages of low cost, minimum impact on facility operations, improved flow quality (in the smaller nozzles) and reduced power requirements, as well as requiring little downtime for implementation (of the smallest nozzle). The primary disadvantage is the limitation on maximum model size.

The second option will provide the background noise desired, but at the expense of aerodynamic losses, significant modifications to the circuit, high initial cost, and increased maintenance.

The third option provides gains in operating efficiency and reduced noise, but by itself does not meet the background noise goal. Moderate downtime would be required.

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┌─────────────────────────────┬─────────────────────────────┐
│                             │                             │
│  ① Maintain Current Fan,    │                             │
│     Flowpath, and Tunnel    │  ③ Rebuild Fan              │
│     Hardware..........      │     to Eliminate            │
│     .......But........      │     Stall, Improve          │
│                             │     Efficiency and          │
│     Test With Smaller       │     Reduce Tip Speed        │
│     Nozzles (add-on's)      │                             │
│                             │                             │
├─────────────────────────────┼─────────────────────────────┤
│                             │                             │
│  ② Maintain Current Fan     │  ④ Rebuild Fan              │
│     ....... But........     │         and                 │
│     Add Acoustic            │     Add Acoustic            │
│     Treatment to Circuit    │      Treatments             │
│                             │       to Circuit            │
│                             │                             │
└─────────────────────────────┴─────────────────────────────┘
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FIGURE 9.   SUMMARY OF BASIC OPTIONS AVAILABLE TO IMPROVE ACOUSTIC
            ENVIRONMENT IN 4X7m TUNNEL

IMPACT ON FACILITY CAPABILITIES AND OPERATIONS

| APPROACH* | BACKGROUND NOISE GOAL | MODEL SIZE LIMIT / MINIMUM ACCEPTABLE | MODEL SIZE LIMIT / CURRENT MAXIMUM | FLOW QUALITY / PLANNED FLOW QUALITY | MAXIMUM $q_o$ / CURRENT MAXIMUM $q_o$ | RELATIVE INITIAL COST | RELATIVE OPERATIVE COST | MAINTENANCE REQUIRED | DOWNTIME FOR CONVERSION | ADDITIONAL STEPS NEEDED |
|---|---|---|---|---|---|---|---|---|---|---|
| ① Maintain Current Fan, etc; Test with Smaller Nozzles | Can Meet | Can Meet (Pending Verification) | Limited to ≈ 0.5 | Improves Due to Increased Contraction | Same (or Higher) | Low | Reduced Power Req'ts | Storage of Nozzles | Virtually None | ● Verify Aero Assumptions ● Verify Fan Noise Reduction ● Design ● Procure |
| ② Maintain Current Fan; Add Acoustic Treatment to Circuit | Can Meet or Exceed | Exceeds | None | Possible Minor Degradation (or Minor Improvement) | May Reduce by 8–10% | High | Increase ∝ $\Delta q/q_o$ | Periodic Cleaning of Certain Treatment | Substantial (to Be Determined) | ● Model Tests ● Design ● Procurement |
| ③ Rebuild Fan | Probably Can't Meet Without Some Treatment in Circuit | Exceeds | None | Could Improve | Could Increase | High | Below Current Costs | Probably Below Current Levels | Substantial (to Be Determined) | ● Model Tests ● Full Scale Flow Measurements ● Design ● Model Test ● Procurement |
| ④ Rebuild Fan and Add Acoustic Treatment to Circuit | Could Exceed Goals by Large Margin | Exceeds | None | Could Improve | Could Increase | High | Below Current Costs | FAN: Less Than Current TREATMENT: Periodic Cleaning | Substantial (take longest of ② or ③) | ② + ③ |

* All choices assume that suitable anechoic treatment will be installed in test section.

FIGURE 10.   SUMMARY OF BENEFITS AND IMPACTS OF FOUR BASIC APPROACHES TO IMPROVING 4x7m TEST SECTION ACOUSTIC ENVIRONMENT

The final option provides the opportunity to meet or surpass the background noise goal with improved flow quality. This option will require high initial costs and substantial downtime.

Clearly, if NASA can limit the maximum model rotor diameter to 6-9 ft, the first option is most attractive. Furthermore, the first option can be implemented in stages, starting with the smallest nozzle and anechoic treatment, almost immediately, and then scheduling the treatment installation required for the larger nozzle for a later time. Otherwise, the fourth option is probably the most attractive.

## 5. RECOMMENDATIONS

(1) Select a major direction for the approach to noise control (from Options 1-4 presented in Sec. 4).

(2) In order to verify the validity of Option 1 and to quantify the benefits of the reduced nozzle size, carry out additional analysis and model tests to verify the predicted relationship between test section area, fan tip speed, and mean flow speed in the first diffuser.

(3) Devise and procure a high quality anechoic treatment for the test section.

(4) Re-examine the question of in-flow acoustic measurements in the context of minimum achievable self-noise levels of microphones as compared with the background noise criterion.

(5) Improve estimates of key variables which are presently dominating the assumptions regarding the required treatment (first and second corner turning vane noise levels, and random incidence performance of various wall treatments).

(6) Carry out model tests and analyses to determine extent to which the fan can be reworked and to quantify the attendant benefit.

(7) Carry out model studies to validate performance of various treatments and optimize their specification.

(8) Once the results of (1), (2), (6) and (7) are in hand, update the specifications of additional noise control treatments.

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# REFERENCE

1.  Hayden, R.E. and J.F. Wilby, "Sources, Paths, and Concepts for Reduction of Noise in the Test Section of the NASA Langley 4x7m Wind Tunnel", NASA CR-172446-1, 1984

# APPENDIX A

## COMPARISON OF FEATURES OF DNW AND 4X7m WIND TUNNELS

## WHICH LEAD TO DIFFERENCES IN TEST SECTION BACKGROUND NOISE

# COMPARISONS OF FEATURES OF DNW AND 4X7m WIND TUNNELS WHICH LEAD TO DIFFERENCES IN TEST SECTION BACKGROUND NOISE

## A.1  Introduction

The DNW subsonic wind tunnel provides a demonstration of background noise levels which can be achieved in a large open-jet, closed-return wind tunnel.  The general arrangement of the tunnel is shown in Figure A.1 (closed jet mode), and the open-jet test section details are illustrated in Figure A.2 (from Ref. A.1).

Figure A.3 (from Ref. 1), illustrates the dramatic difference in test section background noise levels between the DNW facility and the 4x7m wind tunnel (note also that levels shown for the DNW facility is for an 8x6m jet; thus, the DNW fan is providing nearly twice the mass flow as the 4x7m fan for the same test section velocity).  At low frequencies (below 500 Hz), the out-of-flow DNW levels are 25-32 dB lower than those measured on the sideline positions in the NASA 4x7m tunnel.  In-flow levels are not compared since the in-flow data reported by DNW (Ref. A.1) appears to be dominated by flow-induced pressures on their microphones and/or noise radiated from the microphone supports (see App. G of Ref. 1).  This appendix outlines some of the reasons for the large difference between the background noise in the two facilities.

## A.2  Fans

The NASA 4x7m fan has 9 rotor blades with a typical chord of around .6m (2 ft) and an overall diameter of 12.4m; the DNW fan has 8 rotor blades with a typical chord of 1.2m (4 ft) and an overall diameter of 12.35m.  The DNW fan operates unstalled over its entire operating range while the 4x7m fan is stalled in the

*Table 1: Main Design and Performance Data*

| TYPE OF TUNNEL | CLOSED RETURN CIRCUIT (OVERALL LENGTH OF CENTERLINE 320 m) | | |
|---|---|---|---|
| SIZE OF WORKING SECTION | 9.5 x 9.5 | 8 x 6 | 6 x 6 |
| TYPE OF SECTION | CLOSED | CLOSED AND OPEN | CLOSED |
| CONTRACTION RATIO | 4.8 | 9.0 | 12.6 |
| MAX SPEED m/s | 62 | 110 / 90 | 145 |
| STATIC PRESS HE IN TEST SECTION | ATMOSPHERIC 1 BAR | | |
| REYNOLDS NUMBER x 10⁶ | 3.5 | 5.2 | 5.8 |
| MAIN DRIVE | THYR SYNCHR MOTOR NORMAL RATING 12.7 MW | | |
| AUXILIARY DRIVES | MAINLY FOR COMPH AIR 4.7 MW | | |
| FAN | SINGLE STAGE 8 BLADES DIRECT DRIVE 255 RPM CONST PITCH WIND SPEED CONTROL BY MOTOR | | |

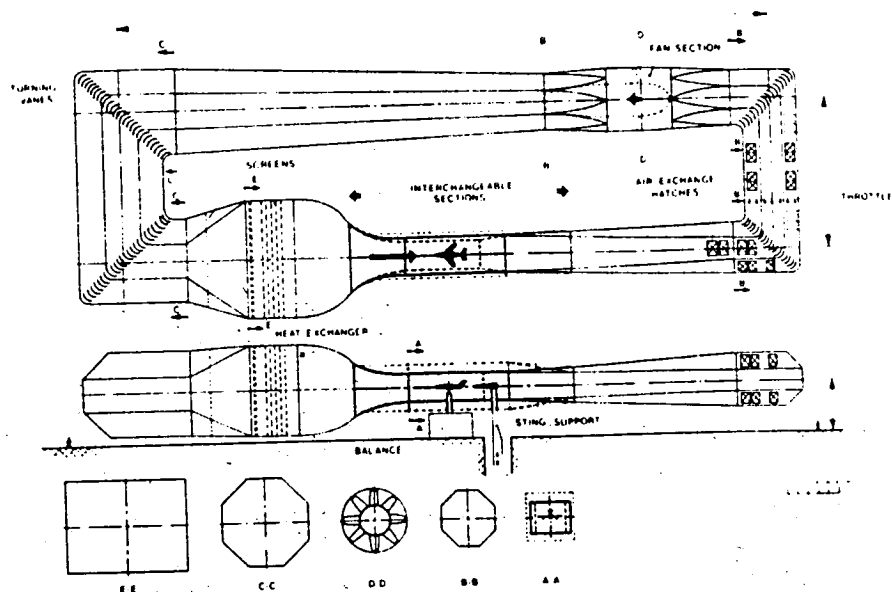*) BASED ON V_max AND 5.1 √A (A TEST SECTION AREA)



FIGURE A.1    OVERALL VIEWS OF DNW LOW SPEED WIND TUNNEL IN CLOSED JET MODE
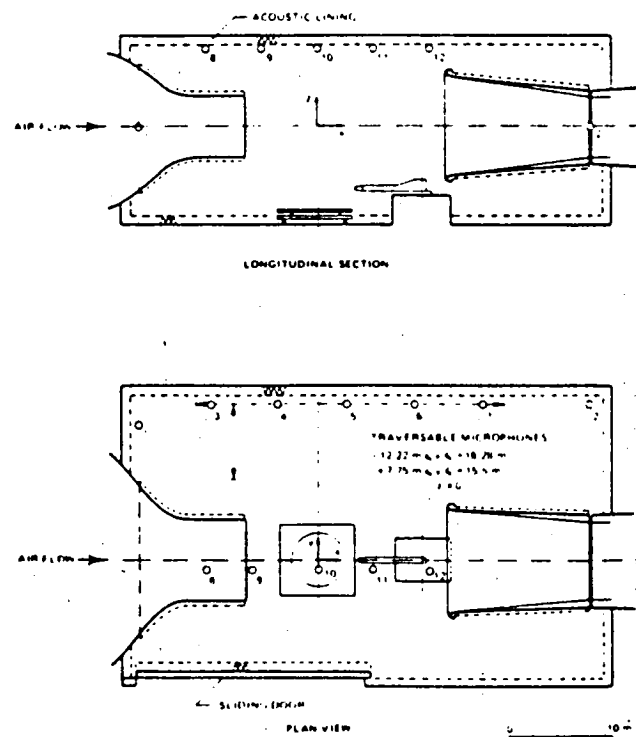
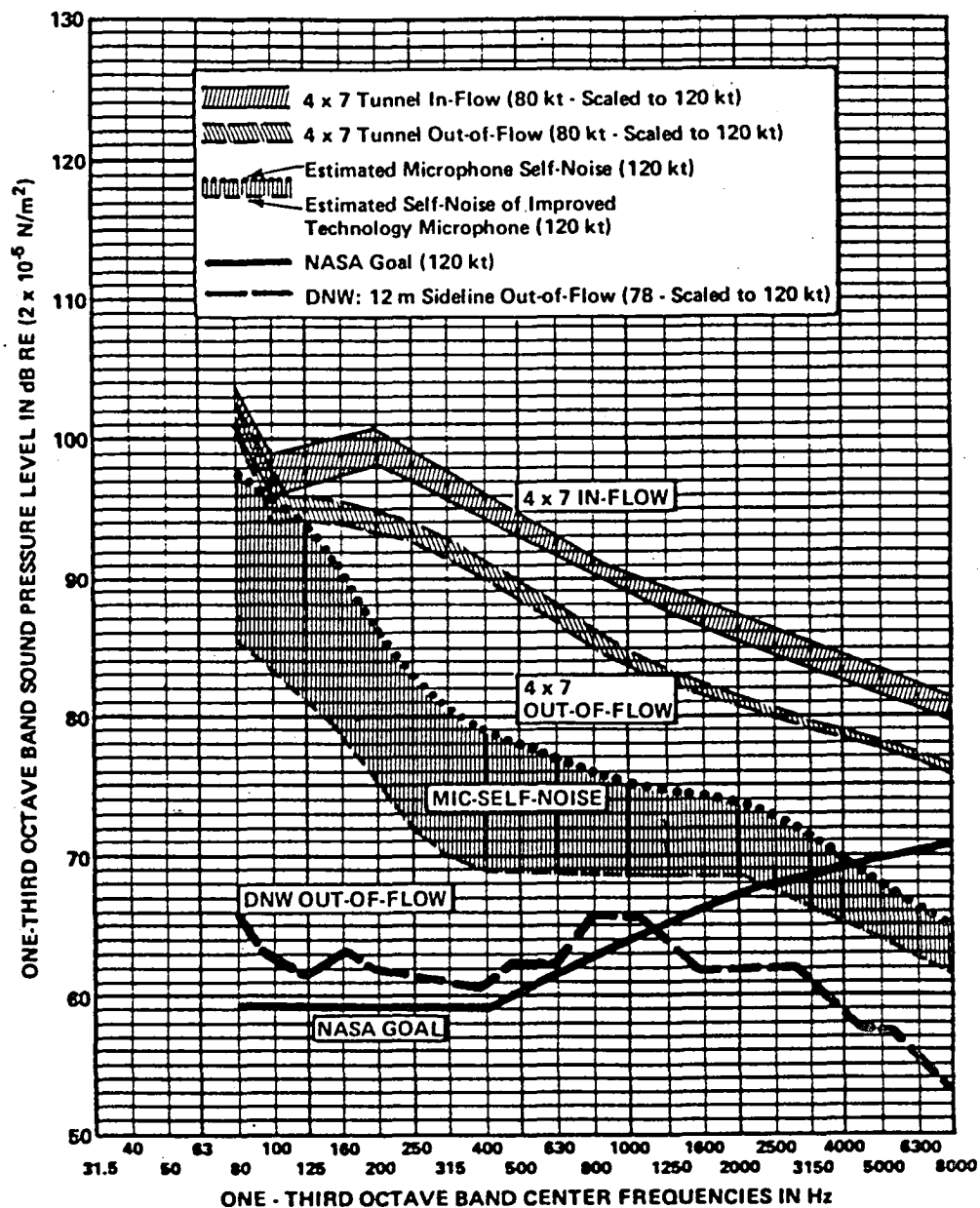FIGURE A.2   OPEN TEST SECTION CONFIGURATION — DNW TUNNEL

FIGURE A.3 COMPARISON OF INTERIM NOISE GOAL, DNW, AND 4X7m TUNNEL BACKGROUND LEVELS AT 80 KT.

outer 10-20% of the blade radius over all operating ranges. The average local lift coefficients on the DNW fan are around 0.5 or less. The DNW fan tip speed (kinematic) is approximately 1.53 times that of the nozzle exit velocity for the 8x6m nozzle which is used in the open jet mode, while the 4x7m tunnel fan tip speed is approximately 2.0 times the nozzle exit velocity. The DNW fan uses a long streamlined nose cone and a rapid contraction of the flow path just upstream of the fan to reduce the effects of flow separation from the circuit walls and thus provides a more uniform inflow for the rotor. The 4x7m fan has a stubby open front nose hub fairing and the circuit provides no sudden contraction of the flow path upstream of the rotor. The DNW fan was designed with the aid of a scale model replica of the entire circuit and thus the fan details were optimally tailored to the inflow which exists; final adjustments in pitch distribution were made using the scale model tunnel. The 4x7m fan was designed without the aid of inflow data, and apparently was not checked out in model scale and adjusted after the initial design. As a result of the above factors, the DNW fan has achieved an installed efficiency of around 90%, while the NASA 4x7m fan has an installed efficiency of around 75%.

The above-described design features of the DNW fan have led to a very quiet operation relative to the 4x7m fan. Figure A.4 shows a comparison of fan noise measured in the 4x7m tunnel near the second corner and similar data from the DNW fan when it is producing the same exit velocity in the test section (the DNW data shown are derived from unpublished model data appropriately scaled to the full scale situation). Comparison of these two curves shows that for the same test section velocity (not mass flow), the DNW fan is typically 15-20 dB quieter than the 4x7m fan. If the DNW fan speed is brought up to that of the 4x7m, the DNW fan spectrum is increased in amplitude by around 6 dB and shifted toward higher frequencies (by 28%), resulting in
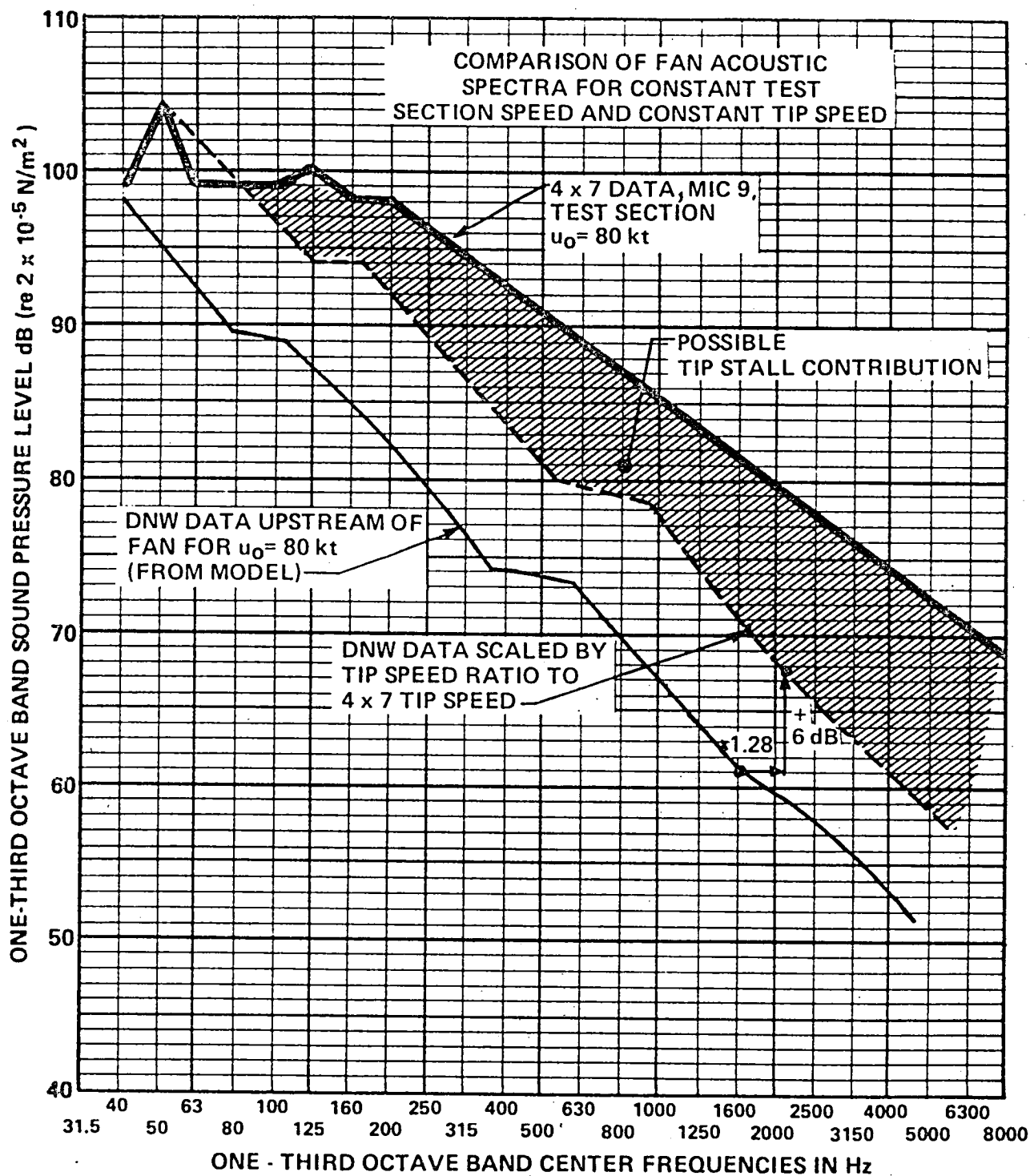
FIGURE A.4   COMPARISON OF FAN NOISE MEASURED UPSTREAM OF FAN
             INLET IN DNW AND 4X7M WIND TUNNELS FOR CONSTANT TEST
             SECTION VELOCITY AND CONSTANT TIP SPEED.

the dashed line shown in Figure A.4. At constant tip speed the
DNW fan is still 6-14 dB quieter than the 4x7m fan. From this
comparison, we might deduce that the difference between the two
spectra is attributable to differences in broadband source
strengths related to the differences in blade loading (see Ref.
1, Sec. 4). Thus, one might view the shaded area as the "stall
noise increment", although some of the differences may lie in the
relative intensity of pressure fluctuations in the attached part
of the flow field. The overlap at the lowest frequencies (for
constant tip speed) may indicate that the dominant mechanism
there is blade response to turbulent inflow, and not stall.

It should be noted that the DNW fan could produce the same
velocity in a 4x7m test section while operating at a lower tip
speed than required for the 8x6m test section (see App. B).
Thus, if the DNW facility were fitted with a 4x7m nozzle, the fan
noise could be as much as 15 dB lower than the present levels, or
a total of up to 30 dB lower than the noise from the NASA 4x7m
fan! It should be noted, however, that the circuit losses in the
DNW tunnel are thought to be around half those in the 4x7m cir-
cuit, and thus the 4x7m fan must produce more thrust to create a
given mass flow in the circuit than would be the case if it oper-
ated in the DNW circuit; therefore the relative improvements of
using the DNW fan in the 4x7m tunnel would be somewhat less than
the maximum values quoted above.

## A.3  Circuit Attenuation (Insertion Loss)

Figure 27 of Ref. 1 showed that in most frequency bands, the
4x7m tunnel had lower insertion loss than the DNW tunnel ("Tunnel
(A)"). However, due to the ambiguities of the insertion loss
("propagation loss") measurements in the 4x7m tunnel, it is not
possible to attribute large differences to the untreated cir-
cuits. However, the DNW circuit has acoustic treatment on the

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first and fourth corner turning vanes which produces at least 10-16 dB insertion loss over and above that provided by the basic circuit (in both directions of propagation).

## A.4 Test Section Acoustic Environment

The DNW test section has complete anechoic treatment, whereas the 4x7m tunnel presently has only limited absorption on some surfaces. Our estimate is that these differences may account for a 5-10 dB reduction in out-of-flow levels in the DNW chamber relative to those existing outside-the-flow when the 4x7m is operated in open jet mode.

## A.5 Summary of Differences Affecting Background Noise in Test Section

The differences between the two facilties in their present open jet configurations for the same exit velocity can be summarized as follows:

| Item | 4x7m Level | DNW level re: 4x7m |
|---|---|---|
| Fan Source Level | Reference | -10 to -20 dB |
| Baseline Circuit Insertion Loss | Reference | small difference |
| Extra Insertion losses | 0 | -10 to -16 dB |
| Test Section Absorption | Reference | -5 to -10 dB |
| TOTAL | Reference | -25 to -46 dB |

This rough comparison provides an adequate accounting of the reasons for the exceptionally large differences between the background noise levels in these two roughly similar facilities and emphasizes the important role of the fan source levels in determining the baseline potential for low noise in a wind tunnel circuit.

# REFERENCE

## for Appendix A

1. van Ditshuizen, J.C.A., G.D. Courage, R. Ross, and K.J. Schultz; "Acoustic Capabilities of the German-Dutch Wind Tunnel DNW", AIAA Paper AIAA-83-0146, presented at AIAA 21st Aerospace Sciences Meeting, January 1984, Reno, Nevada.

# APPENDIX B

## REDUCTION OF SOURCE LEVELS IN WIND TUNNEL CIRCUIT

### BY CHANGING NOZZLE AREA

# REDUCTION OF SOURCE LEVELS IN WIND TUNNEL CIRCUIT BY CHANGING NOZZLE AREA

## B.1. Introduction

When testing scale model rotors in the 4x7m wind tunnel, it may be possible to substantially reduce the cross-sectional area of the nozzle opening and still provide an acceptable flow environment for the rotor (i.e., adequate jet size to prevent ingestion of turbulent shear layers of the free jet). If such a nozzle size reduction could be effected, the noise of the primary sources in the circuit (fan and turning vanes) would be reduced. Such noise reduction is essentially "free", in that no modifications of the circuit or fan would necessarily be required. This appendix outlines an approach to and the benefit from utilizing a (removable) nozzle with reduced exit area for the purpose of carrying out noise measurements on scale model rotors.

## B.2 Required Nozzle Area for Rotor Testing

To avoid shear layer ingestion when testing helicopter rotors in a free jet, the nozzle must have the following geometric characteristics:

$$W > 1.7 \ D_{max};$$

$$H < 0.7 \ W;$$

where W is the width of the rectangular opening,
$D_{max}$ is the maximum diameter of any rotor to be tested, and
H is the height of the nozzle opening.

NASA's plans for the 4x7m tunnel are to usually test 6 ft (1.82m) diameter rotors in the 4x7m tunnel, and occasionally 9 ft (2.72m) rotors. For such rotors, the minimum dimensions of the nozzle would be:

| D; Rotor dia | $W_{min}$; min width | H; Height | Area; Ao $(m^2)$ |
|---|---|---|---|
| 1.82m | 3.1m | 2.2m | 6.8m$^2$ |
| 2.72m | 4.63m | 3.24m | 15.m$^2$ |

The present dimensions of the nozzle opening of the 4x7m tunnel are actually 4.4m high by 6.58m wide – or 28.98m$^2$. Thus the minimum areas for the 1.82m (6 ft) and 2.72m (9 ft) rotors are respectively 23.5% and 51.8% of the existing opening, and these reduced areas produce a corresponding reduction in mass flow rate through the circuit.

## B.3 Effect of Reduced Nozzle Area on Fan and Turning Vane Noise Source Levels

The primary noise sources in the circuit which can be affected by a reduction in the circuit's flow rate are the fan and the turning vanes. The velocity dependence of the acoustic output from these sources was discussed in detail in Ref. 1. It is of interest to see how much reduction in the pertinent veloc- ity (e.g., fan tip speed and local flow velocity near the turning vanes) is associated with a reduction in nozzle exit area, and to estimate the corresponding noise reduction.

## B.3.1 Relationship of fan tip speed to nozzle exit area

To the first order, the wind tunnel drive fan power input ($W_{fan}$) and the circuit losses ($W_{lost}$) are in equilibrium during steady-state operation of the tunnel (ignoring auxiliary air sys- tems, etc.). For the purposes of this analysis, we can roughly separate the losses into those associated with the nozzle ($W_{noz}$) and those associated the remainder of the circuit combined ($W_{circ}$). Thus

$$W_{lost} \approx W_{noz} + W_{circ} \qquad \qquad \text{(B.1)}$$

The circuit losses can be described as

$$W_{circ} \approx K_c \; (1/2 \rho_c V_c^2) Q_T \qquad \text{(B.2)}$$

where $K_c$ is a characteristic loss coefficient for the circuit,

$\rho_c$ is a characteristic density of the air in the circuit,

$V_c$ is a characteristic velocity in the circuit, and

$Q_T$ is the total volumetric flow rate in the circuit
($Q_T = V_c A_c = V_N A_N$).

Similarly, the nozzle losses can be written as

$$W_{noz} = K_n \; (1/2 \rho_N V_N^2) \; Q_T \quad , \qquad \text{(B.3)}$$

where the subscripts N refer to quantities associated with nozzle flow.

Since $Q_T = V_c A_c = V_N A_N$, the circuit power (and thus the fan power required) can be written as

$$W_{lost} = W_{fan} = K_c \; K_c \; (1/2 \rho_c V_c^2) \; (V_c A_c) + K_N \; (1/2 \rho_N V_N^2) \; (V_N A_N) \qquad \text{(B.4)}$$

from which the fan power can be restated as

$$W_{fan} = V_N^3 \left[ K_c(1/2 \rho_c A_c) \; (A_N/A_c)^3 + K_N(1/2 \rho_N A_N) \right] \qquad \text{(B.5)}$$

The fan power ($W_{fan}$) is equal to the product of its thrust, $T_F$, and a characteristic velocity of the circuit, $V_c$, and can be written in terms of its gross blade parameters and its tip speed as

$$W_{fan} = 1/2 \rho_c V_T^2 \; BR \int_{hub}^{tip} C_L(r) \; \cos\beta(r) \; dr \times [V_N(A_N/A_c)] \qquad \text{(B.6)}$$

where $V_T$ is the fan tip speed; B a characteristic chord dimension; R, the tip radius, $C_L(r)$ the local lift coefficient, $\beta$ the

local settling angle, r the distance in the radial direction from the fan centerline, and $V_C$ has been restated as $V_N(A_N/A_C)$.

Through the use of the previously-described relationships, the fan power can be written as

$$W_{fan} \propto V_N^2 A_C [K_C \, 1/2\rho_C(A_N/A_C)^2 + K_N(1/2\rho)] \qquad (B.7)$$

<u>If the circuit losses are strongly dominant over nozzle losses, and if the circuit loss coefficient does not depend strongly on nozzle area</u> (neither of which have been substantiated by the author for the 4x7m tunnel), then

$$\frac{V_T}{V_N} \approx [\frac{A_N}{A_C}] \qquad (B.8)$$

Using this result, it is now possible to estimate the change in the fan noise spectrum which will result from decreasing the nozzle area by either of the amounts determined in Sec. B.2.

Curve A of Figure B.1 shows the 1/3 octave band spectra of fan noise measured upstream of the 4x7m fan in the vicinity of the second corner (Ref. 1, Fig. 44). Curve B shows the estimated effect of eliminating stall, and Curves C and D show the predicted effects of tip speed reductions. These reductions were predicted using a $V^5$ amplitude scaling at constant Strouhal number; thus, in addition to reductions in overall levels, there is additional benefit realized in the frequency band of interest (f> 100 Hz) as a result of the spectrum shifting to lower frequencies. Figure B.2 shows the range of predicted source levels (at the second corner location) for a 48% speed reduction and a 76.5% speed reduction (corresponding to the two nozzle sizes required for the 9 and 6 ft rotors. For each condition, the upper part of the band represents noise from a stalled fan while the lower part is the predicted noise from an unstalled fan. Also shown on Figure B.2 is the test section background noise specification
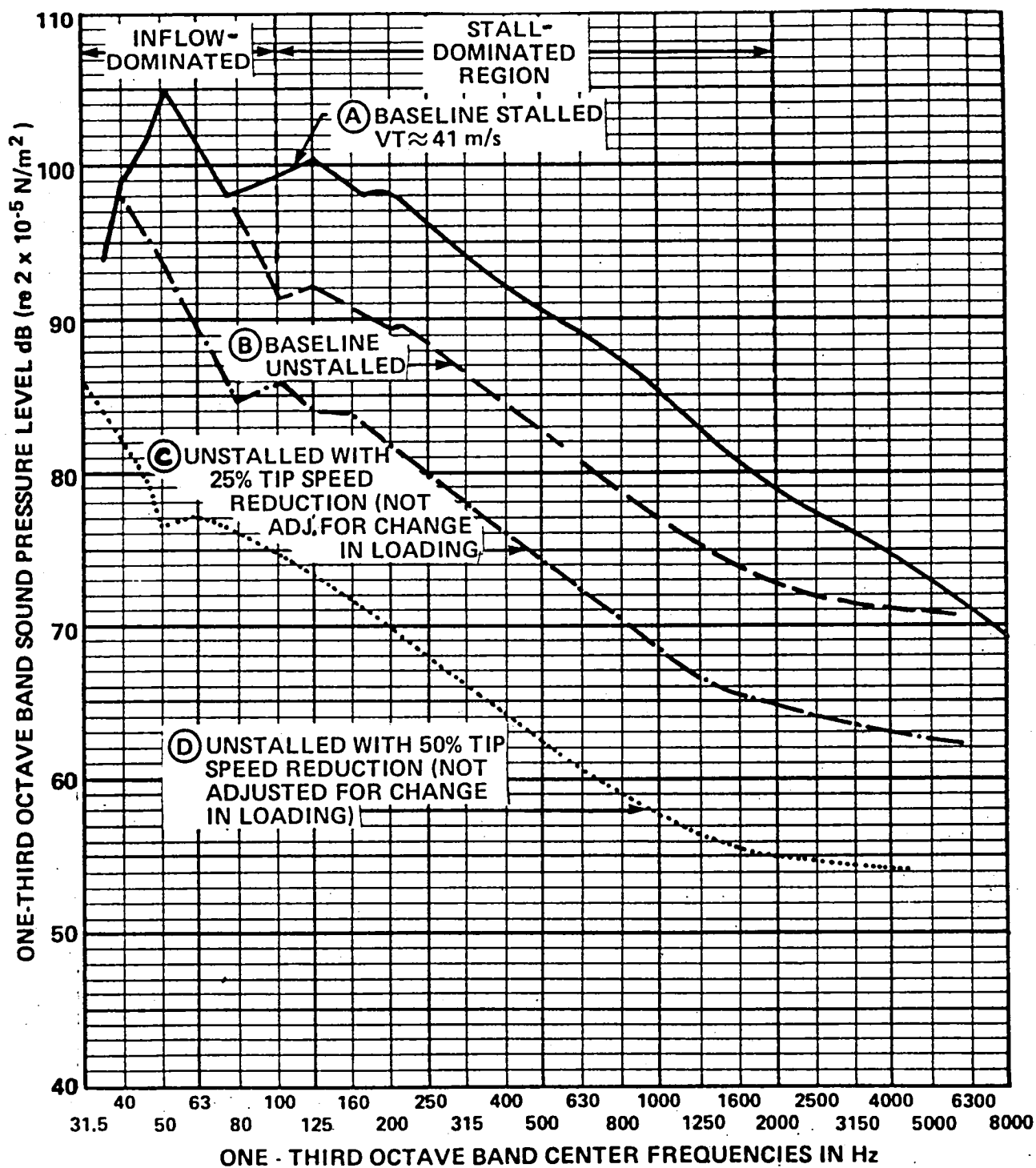
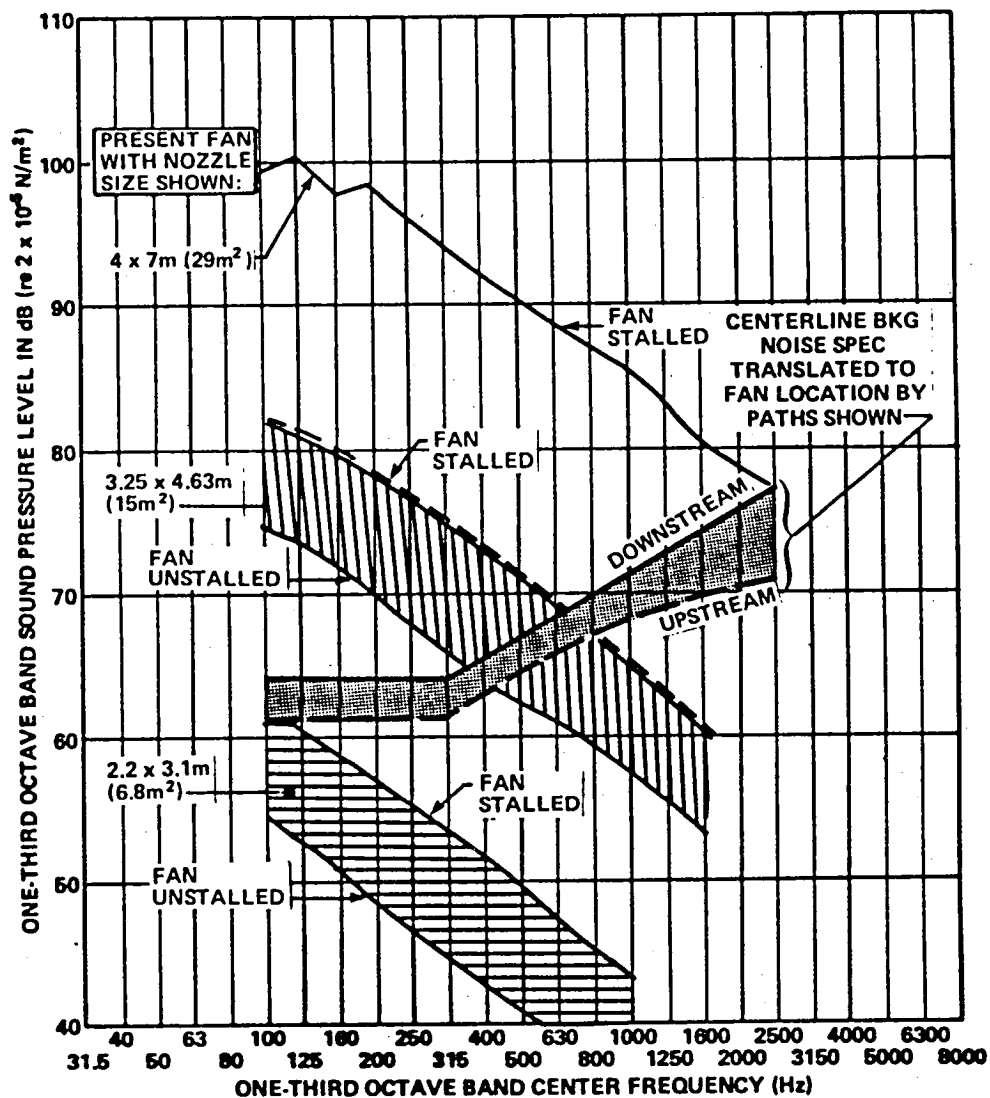FIGURE B.1 COMPARISON OF SPACE-AVERAGED SPL FROM 4X7M FAN FOR SEVERAL CONDITIONS (FROM REF. 1.)

FIGURE B.2   RANGE OF FAN NOISE LEVELS AT SECOND CORNER PRODUCED
BY CIRCUIT MASS FLOW REDUCTION

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projected to the second corner location using the circuit insertion loss spectrum derived in Ref. 1 (also referred to as "propagation loss"). Comparison of the predicted source levels with this "translated" specification shows that <u>no</u> reduction of fan source levels would be required for the 6.8m$^2$ nozzle (i.e., for tests of 6 ft rotors) and a relatively small reduction would be required for the 15m$^2$ nozzle (for tests of 9 ft rotors) <u>if the fan was unstalled</u>. Note also that there is an additional 10 dB of insertion loss for the out-of-flow microphone positions when an anechoic treatment is used. Thus, for out-of-flow microphone positions, even the configuration using the larger nozzle has fan noise levels which meet the background noise goal at frequencies above 400 Hz.

## B.3.2 Relationship of turning vane noise to nozzle exit area

Reference 1 predicted test section background noise levels from the first and second corner turning vanes which were 15-25 dB below those contributed by the fan. The turning vane noise at constant Strouhal number is proportional to $V_c{}^5 - V_c{}^6$, where $V_c$ is a characteristic local velocity in the circuit. If the first diffuser performs effectively with reduced size nozzles, then the characteristic velocities at the first and second corners will be reduced in direct proportion to the ratio of the smaller nozzle area to the original nozzle are (for a given exit velocity). If that is the case, the turning vane contributions will remain 15-25 dB below fan contributions and will be near or below the NASA test section background noise criterion at all frequencies out-of-the flow and at all but the lowest frequencies in the flow. If however, the diffuser stalls and allows the high velocity jet to penetrate further down the diffuser toward the vanes, then the noise levels will be in a range between the present levels and those which would be predicted by the simple $V_c{}^{5-6}$ scaling at constant Strouhal number. In such a case, the vane noise could

exceed the NASA criterion. However, if model or full scale tests showed that the diffuser was not performing with the smaller nozzles, a "portable" or removable diffuser entrance (collector) could be built to accomodate the transition between the smaller nozzle and the existing diffuser.

## B.4   Schematic Concepts for Implementation of Reduced-Size Nozzle Approach

The implementation of the reduced-size nozzle approach to meeting background noise goals requires only removable nozzles (probably made with fiberglass) which can be mated to the existing 4x7m nozzle. Such nozzles are quite portable and probably can be installed in much less time than required for normal model rotor setups. A portable (removable) collector may also be required if the present collector and diffuser system does not perform adequately with the smaller nozzle.

Figures B.3 and B.4 show schematics of the two nozzles, specified in Sec. B.2, installed on the 4x7m nozzle. The only difference between Figs. B.3 and B.4 is the assumed orientation of the rotor. Also shown in these figures are wedges and flat-faced absorbing material representing the acoustic treatment required for the test chamber to improve its acoustic characteristics.

Note that with the small nozzles, two additional benefits may be expected:

(1)   There will be reduced flow impingement on the floor of the test chamber, thus reducing sound generation associated with that process and allowing for a greater depth of acoustic treatment there, and

(2)   It may be possible to retain the existing control room location since the nozzle extensions move the test

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(320.00)

── NOZZLE A = 2.2 x 3.1 m = 6.82 m²
---- NOZZLE B = 3.25 x 4.64 = 15.1 m²

POSSIBLE PORTABLE
ADDITION TO
PLANNED COLLECTOR

⊢ 20' ⊣
APPROXIMATE
SCALE
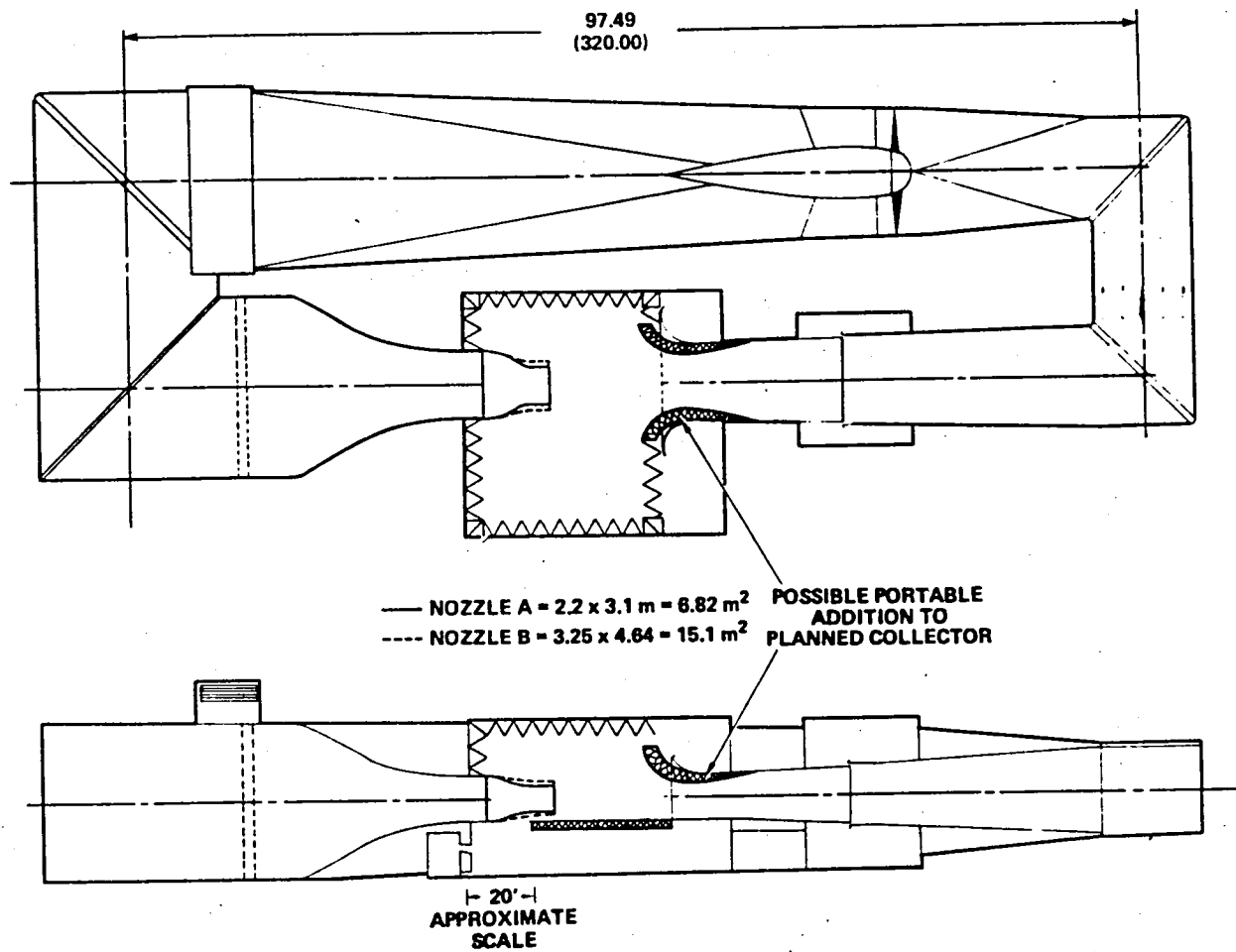
FIGURE B.3   SCHEMATIC OF 4X7m TUNNEL FITTED WITH REDUCED SIZE
NOZZLES (FOR HORIZONTAL ROTOR PLANE)

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(320.00)

— NOZZLE A = 2.2 x 3.1 m = 6.82 m$^2$
---- NOZZLE B = 3.25 x 4.64 = 15.1 m$^2$

POSSIBLE PORTABLE
ADDITION TO
PLANNED COLLECTOR

⊢ 20' ⊣
APPROXIMATE
SCALE

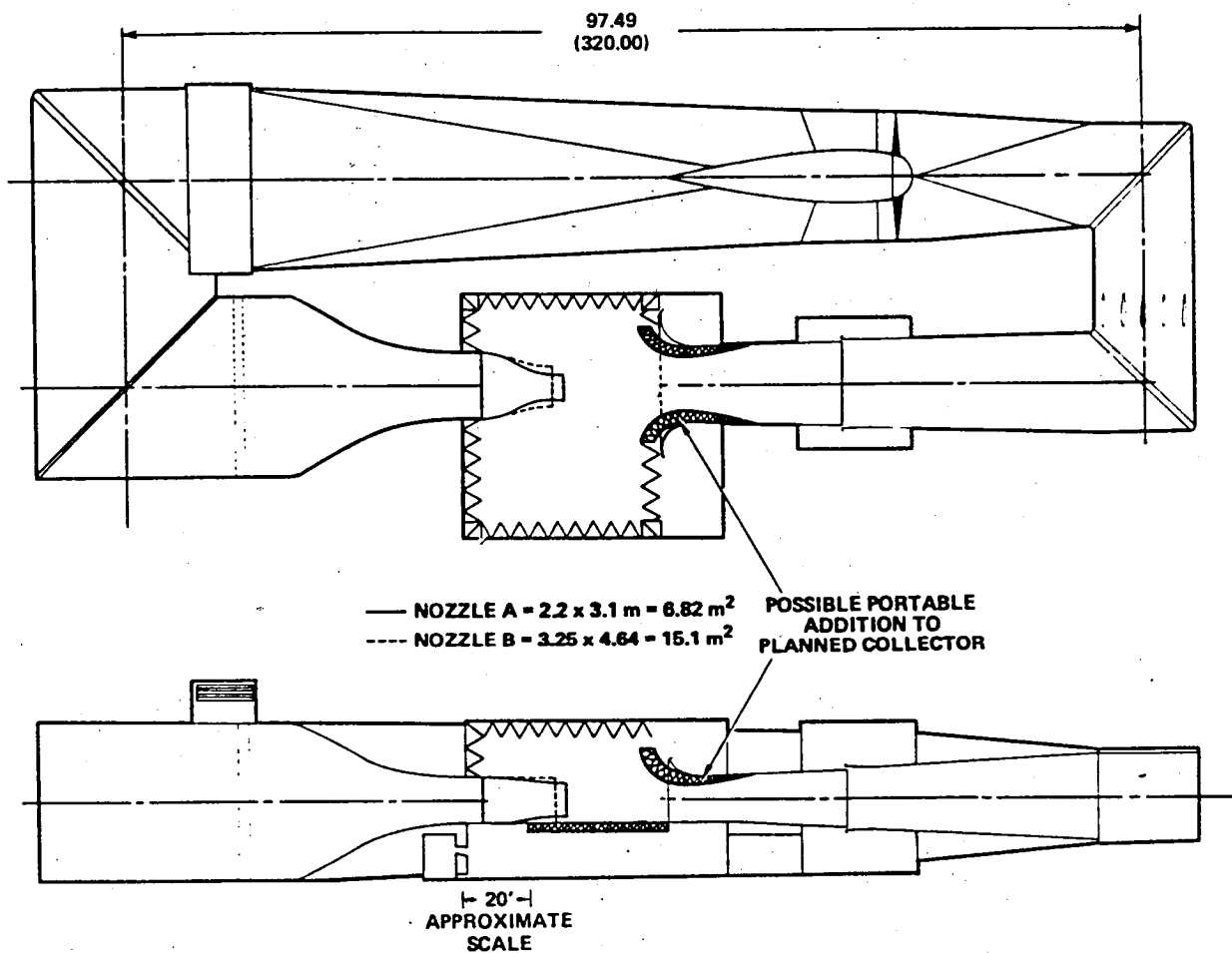FIGURE B.4   SCHEMATIC OF 4X7m TUNNEL FITTED WITH REDUCED SIZE
NOZZLES (FOR VERTICAL ROTOR PLANE)

object away from the control room and thus allow for an
adequate depth of acoustic treatment to be placed there.

## B.5 Summary

It has been shown that substantial reduction of background
noise in the 4x7m tunnel test section can be achieved by use of
(portable and temporary) add-on nozzles having reduced exit area.
If the assumption that circuit losses dominate nozzle and collec-
tor losses and that the circuit loss coefficient does not
increase with reduced volume flow, then it is predicted that both
fan and turning vane noise should be reduced in direct proportion
to the fifth-power of the ratio of the reduced nozzle area to the
original area; these sound power reductions occur at constant
Strouhal number (normalized frequency) and thus, at a given
frequency, additional reductions will occur as a result of the
shifting of the spectrum of noise produced by the fan and turning
vanes. It is estimated that for a nozzle suitable for testing
1.82m (6 ft) diameter rotors, enough source noise reduction can
be achieved to alleviate the requirement for _any_ other acoustic
treatment in the circuit.

A scale model test is recommended to verify the fan speed
reduction assumptions collector and diffuser performance, and
turning vane noise.

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15. Supplementary Notes

(1) NASA Technical Monitor: Dr. John P. Raney
(2) Final Report

16. Abstract

This report is a supplement to NASA CR             .  The present report compares acoustically significant features of the NASA 4x7m wind tunnel and the Dutch-German DNW Low Speed Tunnel to illustrate the reasons for large differences in background noise in the open jet test sections of the two tunnels.  Also introduced in this report is the concept of reducing test section noise levels through fan and turning vane source reductions which can be brought about by reducing the nozzle cross sectional area, and thus the circuit mass flow for a particular exit velocity.  A complete review of the costs and benefits of treating sources, paths and changing nozzle geometry is provided.

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